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BROADBAND LASER FILTER

FINAL, PHASE I REPORT

JOHN A. BROWN

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John Brown Associates, Inc.
P.O. Box 145
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P.O. Box 145
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13. ABSTRACT *(Maximum 200 words)*

There is a growing need to provide eye protection to military personnel at risk from laser beams, many of which have the ability to blind a person by burning the retina.

This program has taken a new approach to protective filters: an optical interference filter that blocks the entire visible spectrum except for three narrow transmission bands, one in the red, one in the green and one in the blue. The new filter blocks all of the currently-identified threat wavelengths as well as some that have not (yet) been identified as threats.

The total light transmission is only 6%; and yet, since the wavelengths passed are essentially the primary colors of human vision, vision through the filter is bright and clear and in full natural color. In highway testing behind the wheel of an automobile, visual acuity was excellent; red lights were red; the yellow line was yellow; the blue sky was blue; and white cars were white. But laser threat wavelengths could not be seen.

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The work was carried out by Dr. John A. Brown, president of John Brown Associates, and Dr. William A. Thornton, an ad hoc associate. Dr. Thornton did the theoretical studies that led to the initial tristimulus concept, and Dr. Brown carried out the engineering and development portions of the program. This report was written by Dr. Brown.

BROADBAND LASER FILTER

2. INTRODUCTION

2.1 The Battlefield Laser Threat

There is a growing need to provide eye protection to military personnel at risk from laser beams, many of which have the ability to blind a person by burning the retina; and a number of approaches have been explored by a number of investigators.

Most approaches to date have been notch filters designed to be opaque to specific laser wavelengths but to transmit as much of the rest of the visible spectrum as possible. Examples include holographic interference filters such as the one illustrated in Figure 1 and absorptive dye filters such as the one illustrated in Figure 2 at the end of this Section.

But a notch filter is not a complete answer to the problem, because hostile laser beams may be at unexpected wavelengths. A number of threat wavelengths have already been identified, and new ones are still being identified as new lasers are developed. The threats are classified and so will not be discussed here. The significance of the various filter wavelengths will be evident to readers with appropriate clearance and need-to-know.

2.2 An innovative approach to ocular protection

This program has taken a completely different approach: an interference filter that blocks ALL of the visible spectrum except for three narrow transmission bands as shown in the transmission spectrum in Figure 3. Such a filter would block all of the currently-identified threat wavelengths as well as some that have not (yet) been identified as threats; and yet, since the wavelengths it does pass are esssentially the primary colors of human vision, vision through the filter would be expected to be bright and clear and in full natural color. The phenomenon is analogous to the presentation of a full-color picture by a television picture tube that actually emits only three narrow-band colors: red, green and blue. The principle is simple and clear; the problem is how to make such a filter.

2.3 Specific program objectives

The SBIR proposal that led to this program had four specific objectives:

> Fabricate an optical filter opaque all across the visible spectrum except for three narrow passbands, one in the blue, one in the green and one in the red. The passbands were to avoid all thus-far identified laser threat wavelengths.

Evaluate a human observer's ability to see details and color through the prototype filter at various light levels.

Critique the prototype filter against military criteria and determine what additional R&D would be needed to optimize it and integrate it into suitable military eyewear.

Plan the further R&D and the manufacturing advances that would be needed for full-scale production at an affordable cost.

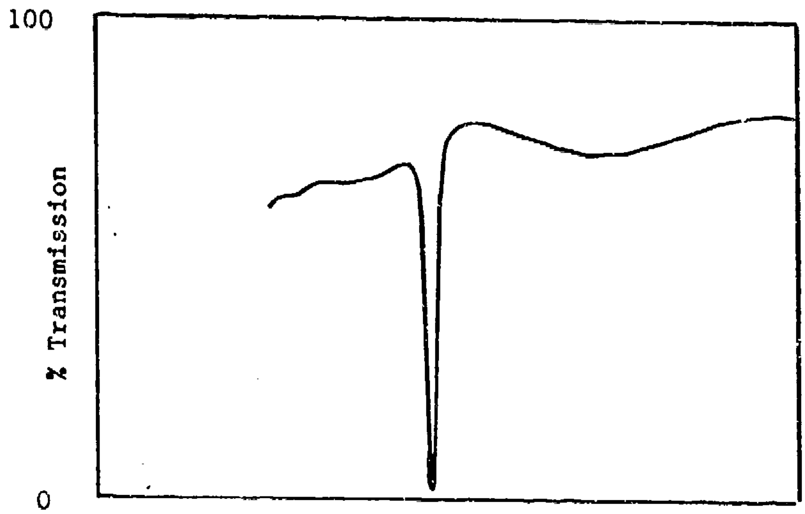


FIGURE 1 - HOLOGRAPHIC NOTCH FILTER

FIGURE 2 - ABSORPTIVE DYE NOTCH FILTER

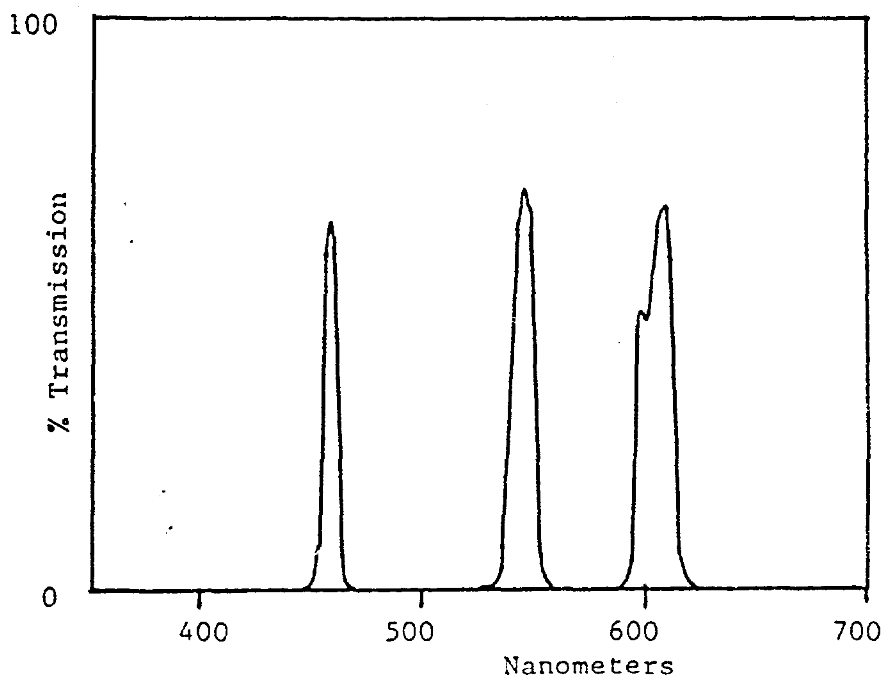


FIGURE 3 - THREE-BAND INTERFERENCE FILTER

3. THE DEVELOPMENT OF BROADBAND FILTERS

3.1 Design approach

The key to this development was a previous finding by one of us (Thornton) that a human observer does not need the entire visible spectrum in order to see well and in full color, but needs only three narrow spectral bands, one in the red, one in the green and one in the blue.

The general approach to tristimulus filter design was to overlay a number of separate interference filters, each designed to block a different, limited, region of the visible spectrum (bandstop filters), and so chosen as to leave narrow passbands between the blocked regions. It was decided to avoid absorptive dyes if possible because of dyes' well-known susceptibility to bleaching, saturation and fading with time.

A large number of different bandstop combinations are possible, and a typical combination that works well is presented in the appendix. However, in most of this work we actually used a design modified from a proprietary design developed some years ago for use in color photography by our coating subcontractor, Omega Optical Inc. Omega made it available to us on a proprietary basis with authorization to use it for second sourceing if our needs should ever exceed Omega's production capability. Omega and we are continuing to work together on an IR&D basis to develop still better designs.

3.2 Filter fabrication techniques

The actual fabrication of the filters is conventional. They are made by high-vacuum evaporation of thin layers of alternating high- and low- refractive index materials such as zinc sulfide and cryolite onto a glass substrate under computer monitoring and control to ensure the correct layer thicknesses. The substrate is rotated in a planetary motion to assist in obtaining optical uniformity of the layers, and the thickness of the layers is critical. Vacuum coating of this delicacy is more of an art than a science, and a highly skilled operator is required. Even with a highly skilled operator, not every attempt is successful.

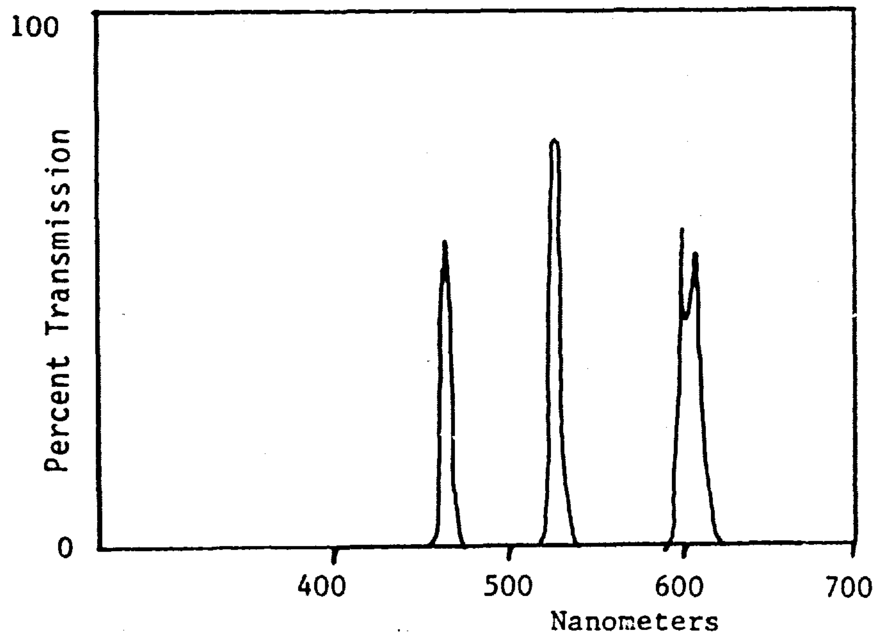
When a successful run is completed, a second plate of glass is laminated on top of the evaporated stack with optical cement, and the final filter is cut to size and edge-sealed. The glass may be clear, or it may be an infrared-absorbing glass such as Schott KG5 or other.

3.3 Fabrication of laser-protective eyewear

During this program, all interference filters were trimmed to two-inch diameter circles to fit into standard vinyl goggle frames made by the Sellstrom Company for conventional laser and welding protection. These goggles are very good for quick evaluations. They fit comfortably over standard eyeglasses and fit snugly around the side of the face to shut out peripheral light. They are ventilated and can be worn for extended periods of time. However, they do limit peripheral vision to an unacceptable degree; and the development of wrap-around eyewear like the ski goggles pictured in Appendix III would be much better.

3.4 Spectral performance of the filters

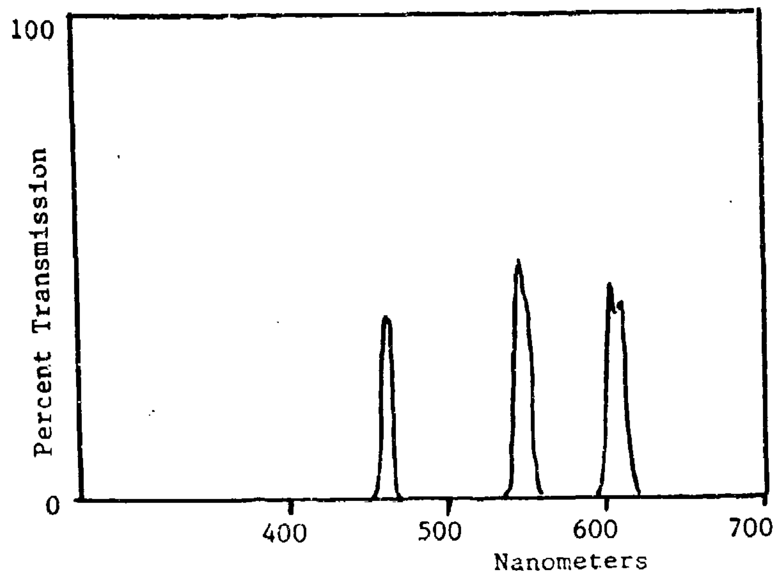
Filter "VIM-1" was an initial experiment to confirm that a three-passband optical filter would indeed permit good color vision. It was actually made (with private funds) between the time the proposal was offered and the time it was accepted. The experiment succeeded, and yielded an optical filter with the transmission spectrum shown below. In this experiment, no attempt was made to place the passbands at optimum wavelengths.



PROTOTYPE THREE-PASSBAND OPTICAL FILTER

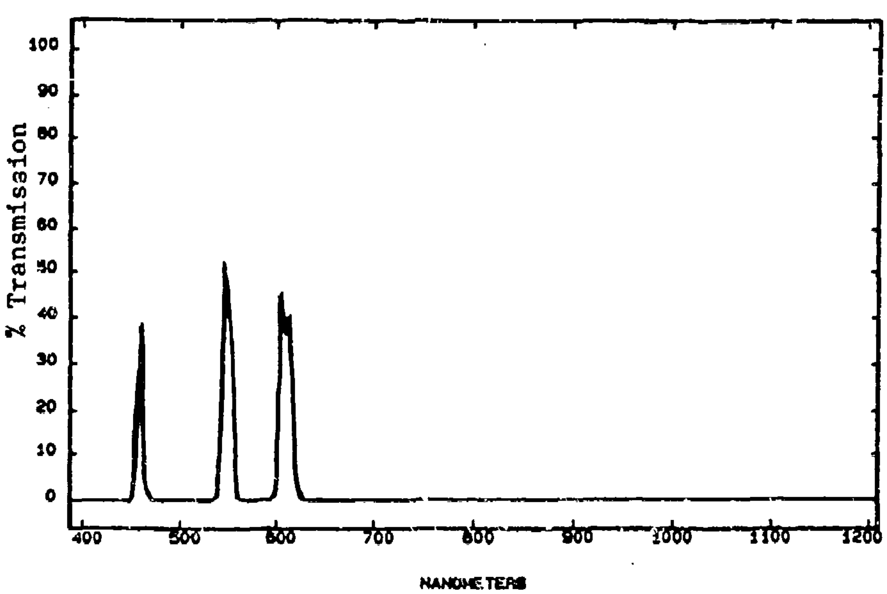
Note that VIM-1 is a technology demonstration, not a laser-protective filter. It does not block all of the laser threat wavelengths.

With the principle and the technique confirmed, Filter "VIM-2" was then designed to have passbands as near as possible to the optimum vision wavelengths while blocking all of the currently-identified laser threat wavelengths and transmitting the important P-43 phosphor emission wavelength. VIM-2's tramsmission spectrum is shown below:



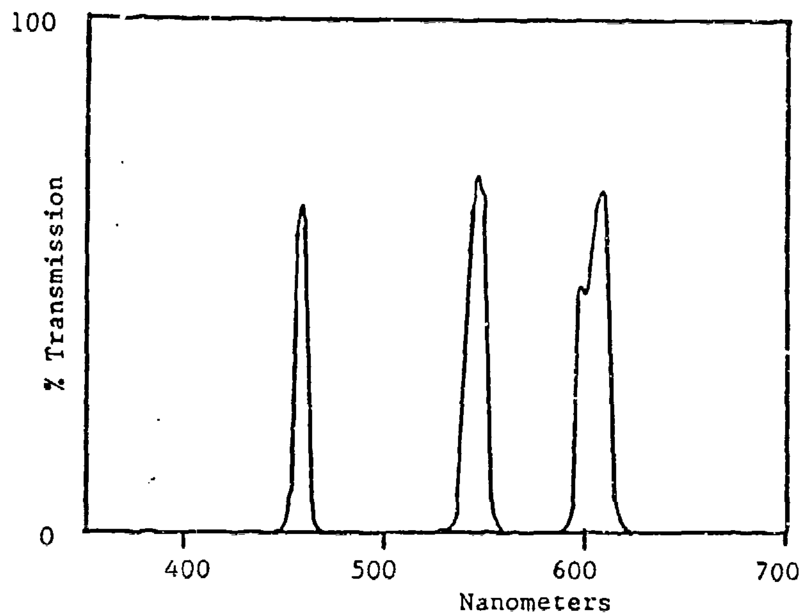
VIM-2 LASER-PROTECTIVE FILTER

VIM-2, being made on KG5 glass (as distinguished from VIM-1's clear glass), also blocks infrared radiation out to at least 1200 nanometers:



VIM-2 LASER-PROTECTIVE FILTER

A third filter, VIM-3, of the same design as VIM-2, was made on clear glass to remove the effect of the somewhat colored KG3 glass of VIM-2. VIM-3's transmission spectrum is shown below:



VIM-3 LASER-PROTECTIVE FILTER

3.5 Visual acuity and color perception

Vision through all of the filters was astonishingly good. Even though the overall light transmission (as the area under the transmission bands) was only approximately 6% of the incident light, vision through all of the goggles was bright and clear. In testing on the highway behind the wheel of an automobile, visual acuity was excellent and outdoor scenes were in full natural color. Red lights were red, the yellow line was yellow, the blue sky was blue, and the green grass was green. The effect was like that of wearing a pair of fine sunglasses.

It is particularly striking that one sees yellow objects as yellow even though the filters transmit no yellow wavelengths. The explanation is that the sensation of yellow does not require spectral yellow. Most "yellow" pigments are spectrally only minus-blue which the human visual system interprets as yellow. A yellow LED emitting at 580 nanometers is not seen through the filter, but a yellow flower is seen.

The phenomenon is directly analogous to the working of a color television picture tube which displays scenes in full perceived color using only three actual emission wavelengths - red, green and blue. At the risk of some oversimplification, the human visual system can be thought of as "sampling" a scene at the three primary colors and reconstructing the full color gamut. It works because pigments are in general broad-band.

3.6 Photopic and scotopic luminance

Direct measurements of "photopic luminance" in a spectrophotometer cannot be made on tristimulus filters because so much of the light assumed by the standard Photopic Sensitivity Curve is deliberately excluded; so evaluations have to be made by actual human observers under realistic seeing conditions.

In daylight, the subjective impression in viewing a scene through VIM-2 for example is that one is looking through about a 20% neutral density filter. VIM-3 gives a somewhat higher number because its total light transmission is somewhat greater due to the absence of the colored KG5 glass. In daylight, particularly bright sunlight, 20% luminance is more than enough for excellent visual acuity and excellent color discrimination. Given a choice, one wears sunglasses to reduce the light intensity.

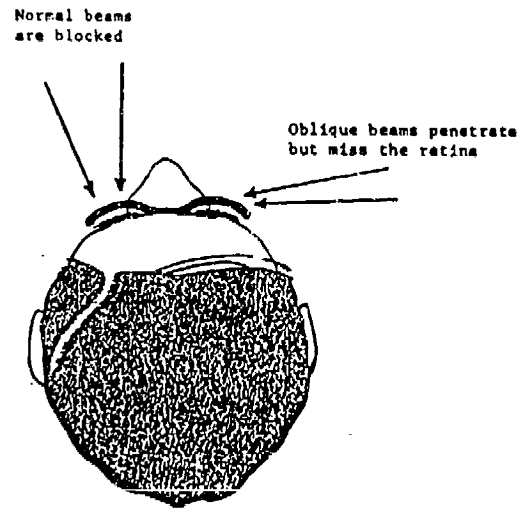
The situation is different at night or in dim light. There, one "wants all the light one can get". One would certainly not wear sunglasses.

Wearing trials in dim light are somewhat inconclusive so far, but they suggest that more light transmission is at least desirable. VIM-3 goggles are comfortable working in a normally-lighted office, but it is more comfortable without them. It is possible to read the small print in a telephone directory through VIM-3 outdoors in deep dusk (about 1.5 footcandles); but not in pre-dawn darkness. One can see one's surroundings reasonably well through VIM-3 at night, but it is difficult to see the stars. The overall conclusion is that more critical evaluations are needed, by the military itself under realistic conditions; and the VIM-3 filter has been provided to the Division of Ocular Hazards at Letterman Army Institute of Research.

3.7 The "angle" effect

All interference filters are subject to what is called the "blue shift" when the incident light beam comes in off-normal, and these tristimulus filters are no exception. The farther off-normal the incoming beam, the greater the blue shift. In a tristimulus filter designed to pass the P-43 phosphor emission line but block the nearby threat wavelength, the angle shift can move the passband right onto the threat wavelength if the incoming beam is far enough off-normal.

There are several potential solutions to the "angle" problem. The most attractive one is to avoid it by using a wrap-around filter so situated that oblique rays will alway miss the eye behind the filter, somewhat like the sketch below. In this arrangement, any incoming ray normal to the filter would be blocked; and any oblique ray that got through would miss the eye.



WRAP-AROUND FILTER CONCEPT

The prospects for fabricating such a wrap-around filter are discussed more fully in Section 4.2, below.

3.8 Overall assessment

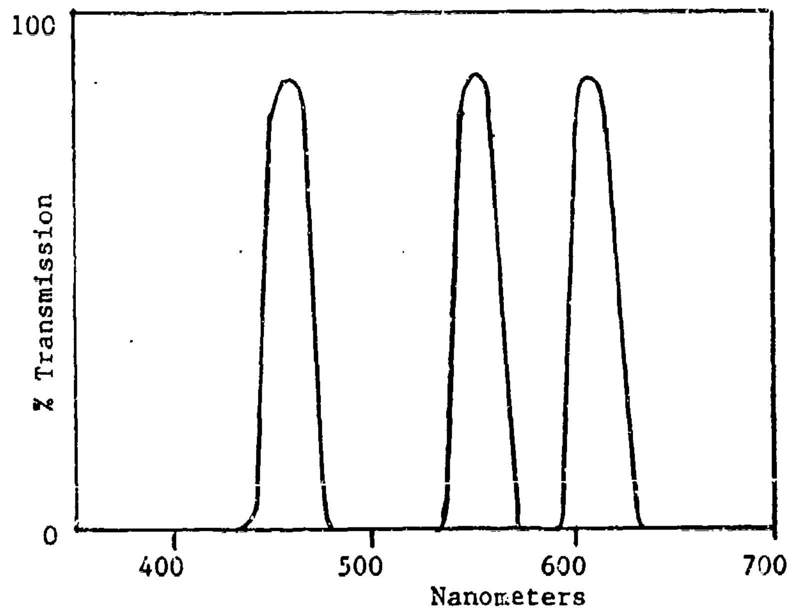
In a nutshell, the feasibility of making a laser-protective optical filter that blocks all currently-identified threat wavelengths (and some that have not yet been designated as threats) while preserving full natural color vision has been demonstrated; and the objectives of the Phase I program have been met. Visual acuity and color perception in daylight are excellent, but need improvement for night use. The blue shift phenomenon common to all interference filters is a problem, but a practical solution is available.

The protective filter known as "VIM-2" could be used by the military as-is, and it would do the job; but it has several shortcomings that ought to be addressed: (1) It is embodied in flat glass, and wrap-around polycarbonate would be better. (2) Greater light transmission would be desirable for use at night or in dim light. (3) The manufacturing cost needs to be reduced. The next section discusses recommended further development work to overcome those problems.

4. FURTHER DEVELOPMENTS RECOMMENDED

4.1 Wider passbands for brighter vision

Greater light transmission than that provided by VIM-2 is at least desirable for night operations, and it can be provided by widening the three passbands as sketched below:



DESIGN CONCEPT FOR A BRIGHTER FILTER

This configuration still blocks all currently-identified threat wavelengths but lets more than twice as much useful light through. Inasmuch as VIM-2 is already at least borderline for night operations, this enhanced version would be expected to be entirely adequate.

Fabrication of the enhanced configuration is the same as that used for the narrow-band filters except that modified bandstop elements leaving wider passbands would be used. Their design, and the deposition of the layers is straighforward and would present no new problems.

4.2 Wrap-around polycarbonate lenses

Polycarbonate lenses and visors are always preferred over glass because of polycarbonates's much greater impact protection. Polycarbonate was not used in the Phase I program because its high coefficient of expansion has defeated most attempts to deposit interference filters on it (they deposit nicely enough, but they crack off as the part cools).

With IR&D funds separate from the contract, we have scouted an approach that promises to circumvent the cracking problem: deposit the interference filter on a very thin plastic membrane such as polyester, and then laminate it between two sheets of polycarbonate. The deposition was successful, but lamination of the fragile thing has not yet been attempted. At this writing, we are practicing lamination with model membranes to maximize our chances of success when we try the real thing.

It is also preferred that protective eyewear be wrap-around style like ski goggles rather than flat panes, and this poses new fabrication problems. It is much more difficult to deposit complex interference filters onto curved surfaces because of the shape of the vapor cloud in the vacuum chamber, and attempting to bend a laminated filter is expected to stretch and disrupt the interference structure in the middle of the laminate. But we have found that the thin membrane structures are flexible enough to be be curved if they are not stretched at the same time; and our approach is to laminate them between two pre-curved polycarbonate sheets. The curved laminate could then be slipped into a standard ski goggle of the kind that has replaceable lenses; and the result would be the desired wrap-around, laser-protective goggle.

This work is being continued at a low level on IR&D funds, and the results will be available to the Phase II program if one is supported.

4.3 Reduction of manufacturing costs

All the tristimulus filters to date have been made one at a time in a research laboratory by professional personnel, and it would of course be prohibitively costly to make them that way in quantity; so a major objective of any further R&D would be cost reduction. Transfer of operations to a production shop (or multiple production shops) would bring the cost down; and ultimately the learning curve should be able to reduce the cost by an order of magnitude.

However, in the spirit of SBIR, we would like to attempt something really innovative. It is conventional technology to apply thin coatings of aluminum and other metals to continuous rolls of Mylar and other films by vacuum evaporation in processes not unlike those used to make optical interference filters - except that the equipment is much larger and produces metallized film literally by the mile. So far as we have been able to learn, no one has ever tried to make optical interference filters in this equipment; but it looks like a logical extention of the art, and we would like to try it. It will certainly have problems, but the potential payoff is the production of tristimulus interference filters as cheap as cheap sunglasses.

4.4 Phase II R&D plan in brief

This report is not the place for a Phase II proposal; but a Phase II plan was one of the stated objectives of the Phase I program, so an overview of that plan is presented herewith. It is written to stand alone.

TENTATIVE PHASE II PLAN

The feasibility of the tristimulus protective filter concept has been clearly demonstrated, but the photopic luminance needs improvement for night operations. The current model looks to the eye like about a 20% neutral density filter - which is fine in the daylight, but it would be most desirable to increase the perceived brightness to something like 50 or 60 percent for night service.

That could be accomplished without sacrifice of laser protection by broadening the three passbands to approximately twice their present bandwith, a move that would also increase the heights of the transmission peaks. The wider bands need careful design to keep them away from threat wavelengths, but there is room in the spectrum to do that and still avoid all current threats. The widening of the passbands is a straightforward task; but of course the new designs need experimental verification.

The "angle" problem needs to be addressed. It appears that that problem could be circumvented by use of a wrap-around polycarbonate design, and it appears that such a design could be fabricated by laminating a very thin optical interference filter between two sheets of pre-curved polycarbonate and slipping the resulting laminate into a standard ski goggle that features replaceable lenses. It looks straightforward, but demonstration is needed.

Progress is needed in manufacturing methods technology. The filters are currently handmade one-by-one by professional personnel, and that makes them too expensive for field issue. One approach to cost reduction is simply the learning curve in multiple fabrication shops, and that can be expected to eventually cut the cost by an order of magnitude; but we would like to try something really innovative.

It is conventional technology to apply thin coatings of aluminum and other metals to Mylar and other films by vacuum evaporation in processes not unlike those used to make optical interference filters - except that the equipment is much larger and produces metallized films literally by the mile. The best known manufacturer of such equipment is Leybold Vacuum Technologies. So far as we have been able to learn, no one has ever tried to make optical interference filters in this equipment; but it looks like a logical extention of the art to us, and we would like to try it.

The work plan, then, has four tasks:

(1) Improve the photopic luminance of the filter by careful broadening of the three passbands.

(2) Continue the development of wraparound polycarbonate filters.

(3) Reduce manufacturing costs by streamlining conventional vacuum deposition operations.

(4) Explore truly innovative manufacturing methods that have the potential of making the filters downright cheap.

Except for Task 4, the above tasks are details - very important details to be sure, but still details, and appropriate tasks for Phase II.

The proposal will contain a detailed cost estimate, but for planning purposes it now looks as if an effective program will require about $500K and a period of performance of about 24 months.

5.5 <u>Estimate of success</u>

Task 1 - Virtually assured since the technology is in hand and only needs to be applied.

Task 2 - Highly probable since membrane filters have been demonstrated and lamination is a straightforward adaptation of existing skills.

Task 3 - Highly probable since practice and the learning curve always produce significant cost reductions.

Task 4 - Speculative, but a spectacular payoff if it succeeds.

APPENDIX I

NEW TECHNOLOGY DEVELOPED

number of new items of technology were developed on this program.

A laser-protective filter that blocks all currently-identified threat wavelengths and yet permits full natural color vision.

An interference filter with three simultaneous passbands. So far as we have been able to learn, this has never been done before.

Optical interference filters on micron-thin plastic membranes. (Development in progress.)

Optical interference filters in a curved polycarbonate lens. (Development in progress.)

nd five patent actions have been initiated:

) FILTER WITH THREE-BAND TRANSMISSION FOR GOOD SEEING, Patent application filed by W. A. Thornton in his name only. Interference action pending.

) TRISTIMULUS COLOR FILTER, Disclosure by J. A. Brown. Patent application pending.

) BLOCKING OF THE "ANGLE SHIFT" IN INTERFERENCE FILTERS, Disclosure by J. A. Brown. Decision on patent filing pending.

) METHOD FOR APPLYING THIN-FILM STACKS ON POLYMER SUBSTRATES, Disclosure by J. A. Brown. Decision on patent filing pending.

) MOSAIC TRISTIMULUS COLOR FILTER, Disclosure by J. A. Brown and J. J. Cronin. Decision on patent filing pending.

APPENDIX II

DESIGNS FOR BANDSTOP INTERFERENCE FILTERS

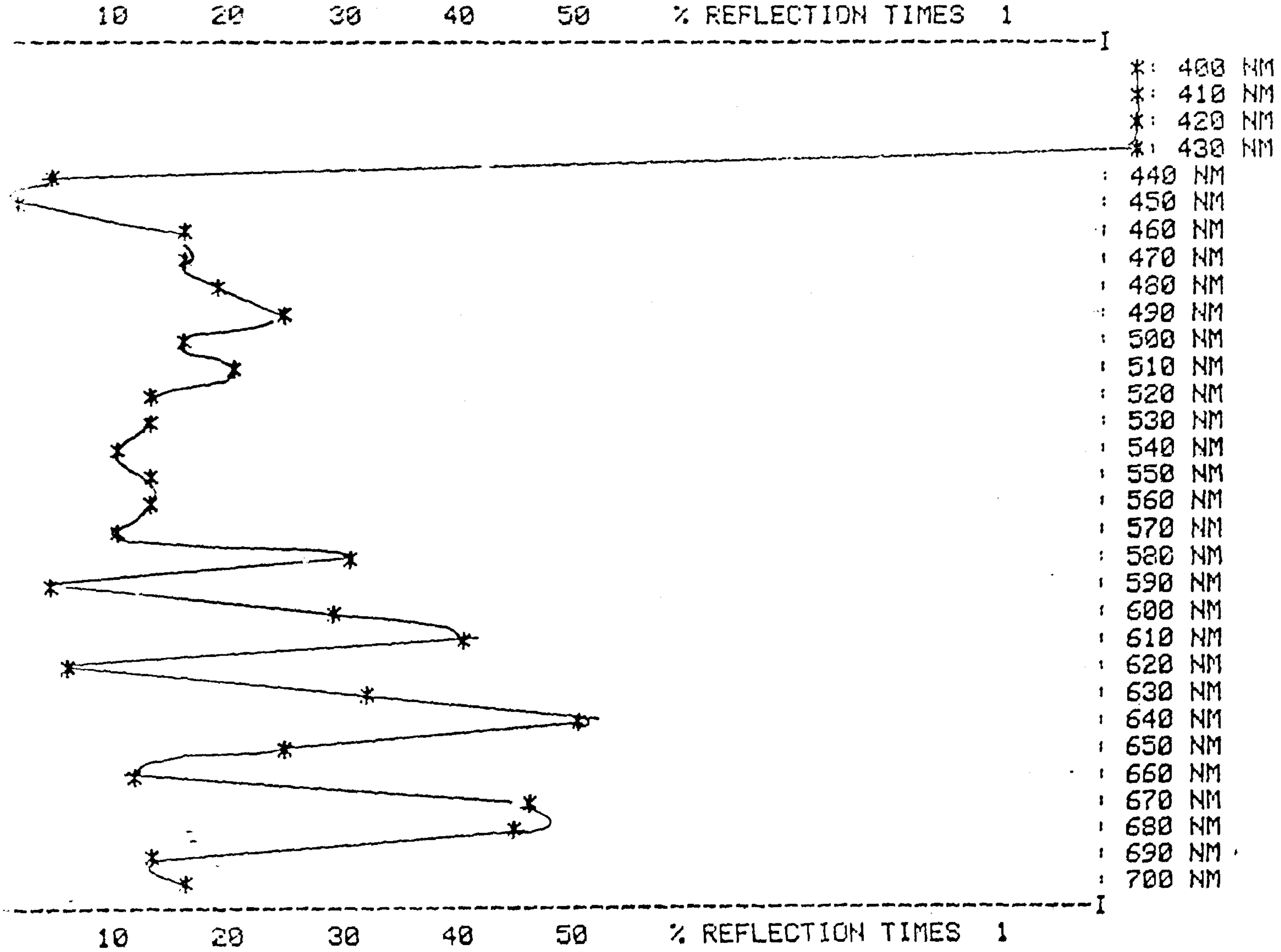
The following four bandstop filter designs will, if stacked on top of one another, produce a tristimulus optical filter similar to the ones called "VIM-1, VIM-2 and VIM-3". That result can be previewed by superimposing the four figures and holding them up to the light, whereupon the three passbands will be clearly evident. The figures are computer simulations.

These elements were not designed to make a laser filter; they were designed to be a general example of a tristimulus filter without any regard to classified threat wavelengths.

REFLECTIVITY OF DIELECTRIC STACK, UNPOLARIZED 0 DEG

REFRACTIVE INDEX OF SUBSTRATE = 1.53

LAYER #	REF INDEX	THICKNESS, NM	QWOTS AT 410
1	2.35	218.1	5
2	1.8	170.8	3
3	2.35	130.9	3
4	1.35	227.8	3
5	2.35	130.9	3
6	1.35	227.8	3
7	2.35	130.9	3
8	1.35	227.8	3
9	2.35	130.9	3
10	1.35	227.8	3
11	2.35	130.9	3
12	1.35	227.8	3
13	2.35	130.9	3
14	1.35	227.8	3
15	2.35	130.9	3
16	1.35	227.8	3
17	2.35	130.9	3
18	1.8	170.8	3
19	2.35	218.1	5



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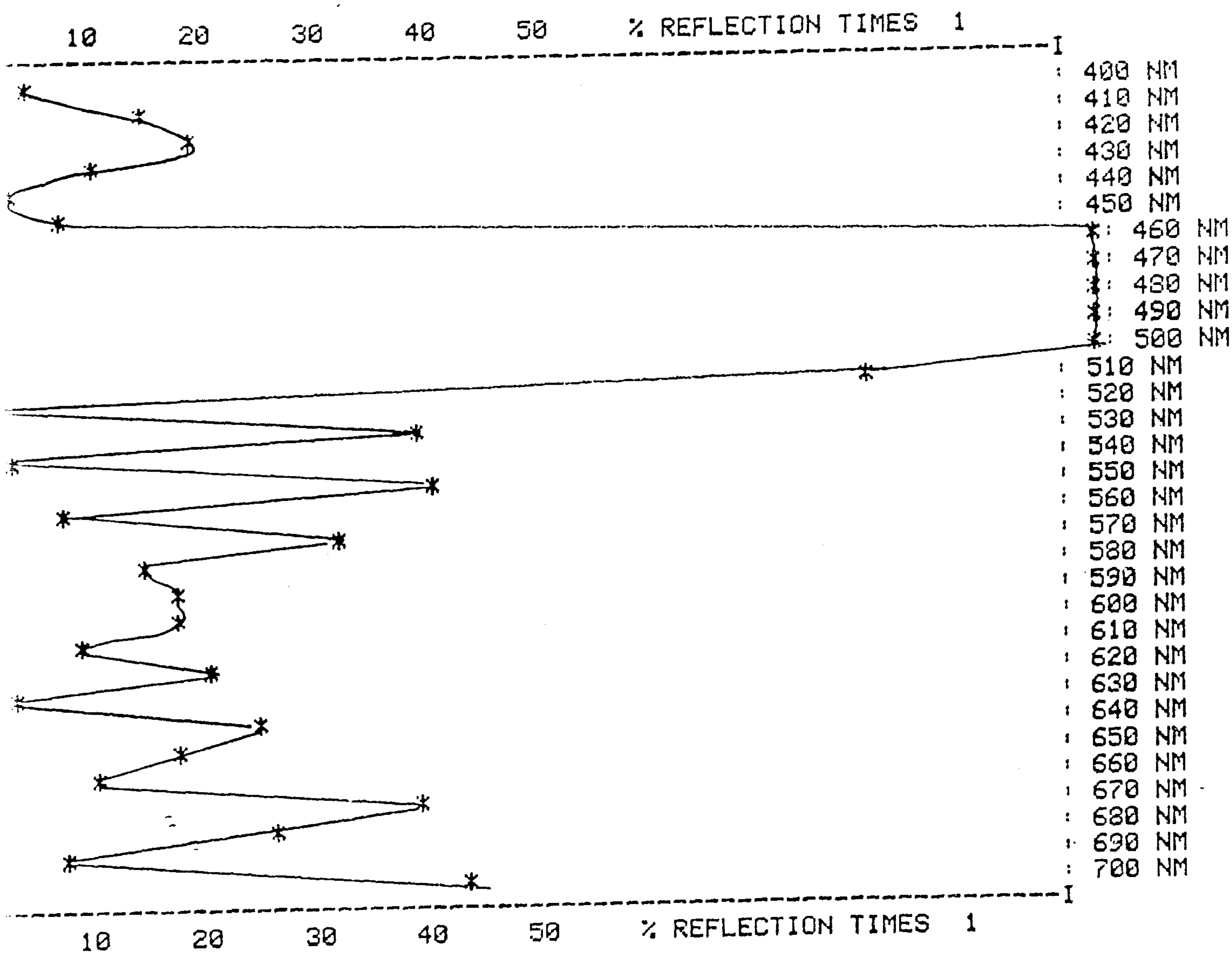
REFLECTIVITY OF DIELECTRIC STACK, UNPOLARIZED 0 DEG

REFRACTIVE INDEX OF SUBSTRATE = 1.53

LAYER #	REF INDEX	THICKNESS, NM	QWOTS AT 480
1	2.35	240	4.7
2	1.8	200	3
3	2.35	153.2	3
4	1.35	266.7	3
5	2.35	153.2	3
6	1.35	266.7	3
7	2.35	153.2	3
8	1.35	266.7	3
9	2.35	153.2	3
10	1.35	266.7	3
11	2.35	153.2	3
12	1.35	266.7	3
13	2.35	153.2	3
14	1.35	266.7	3
15	2.35	153.2	3
16	1.35	266.7	3
17	2.35	153.2	3
18	1.8	200	3
19	2.35	240	4.7



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REFLECTIVITY OF DIELECTRIC STACK, UNPOLARIZED 0 DEG

REFRACTIVE INDEX OF SUBSTRATE = 1.53

LAYER #	REF INDEX	THICKNESS, NM	QWOTS AT 560
1	2.35	297.9	5
2	1.8	233.3	3
3	2.35	178.9	3
4	1.35	311.1	3
5	2.35	178.9	3
6	1.35	311.1	3
7	2.35	178.9	3
8	1.35	311.1	3
9	2.35	178.9	3
10	1.35	311.1	3
11	2.35	178.9	3
12	1.35	311.1	3
13	2.35	178.9	3
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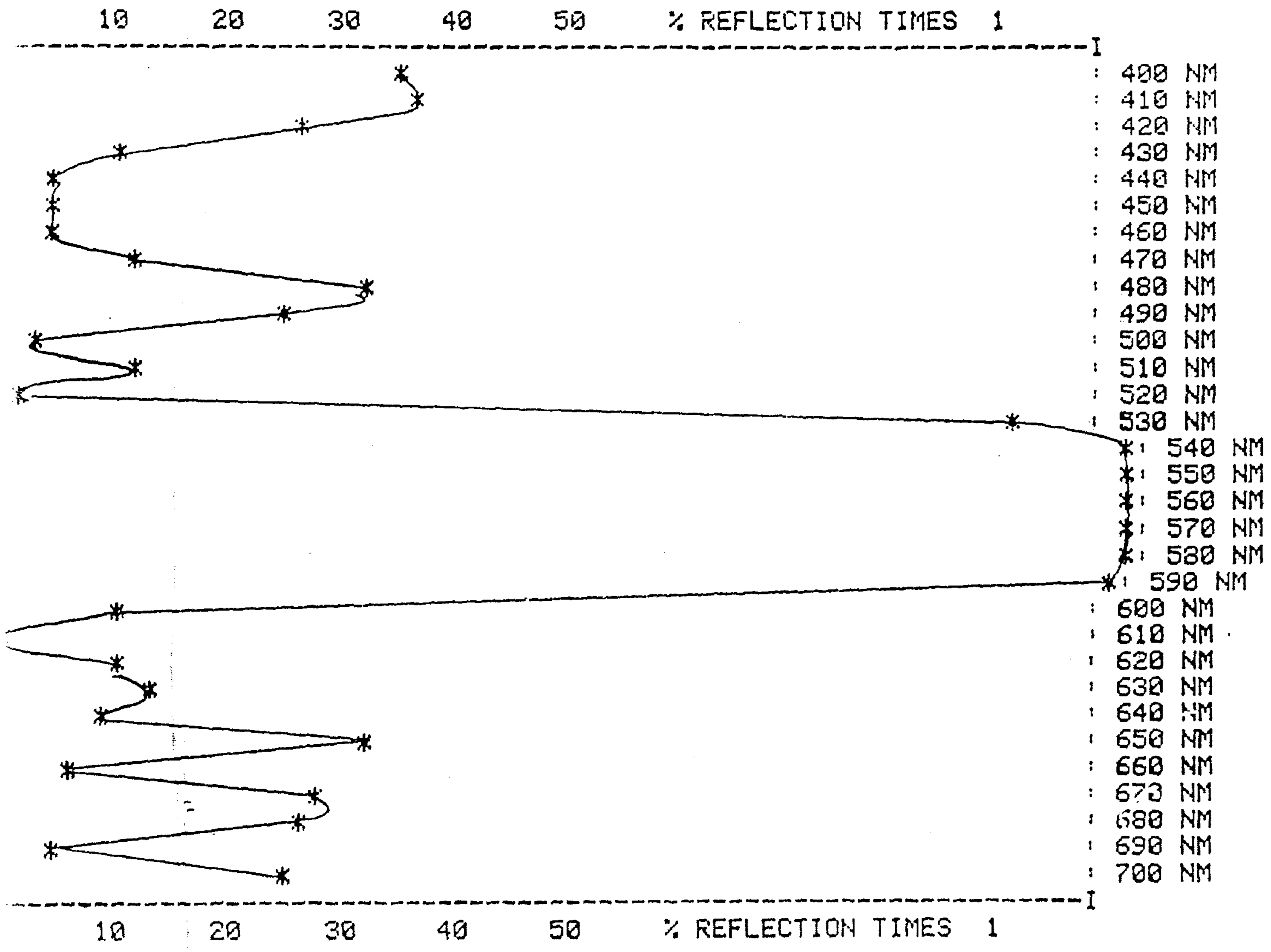
15	2.35	178.9	3
16	1.35	311.1	3
17	2.35	178.9	3
18	1.8	233.3	3
19	2.35	297.9	5



5 FEB 1989

REFLECTIVITY OF DIELECTRIC STACK, UNPOLARIZED 0 DEG

REFRACTIVE INDEX OF SUBSTRATE = 1.53

LAYER #	REF INDEX	THICKNESS, NM	QWOTS AT 650
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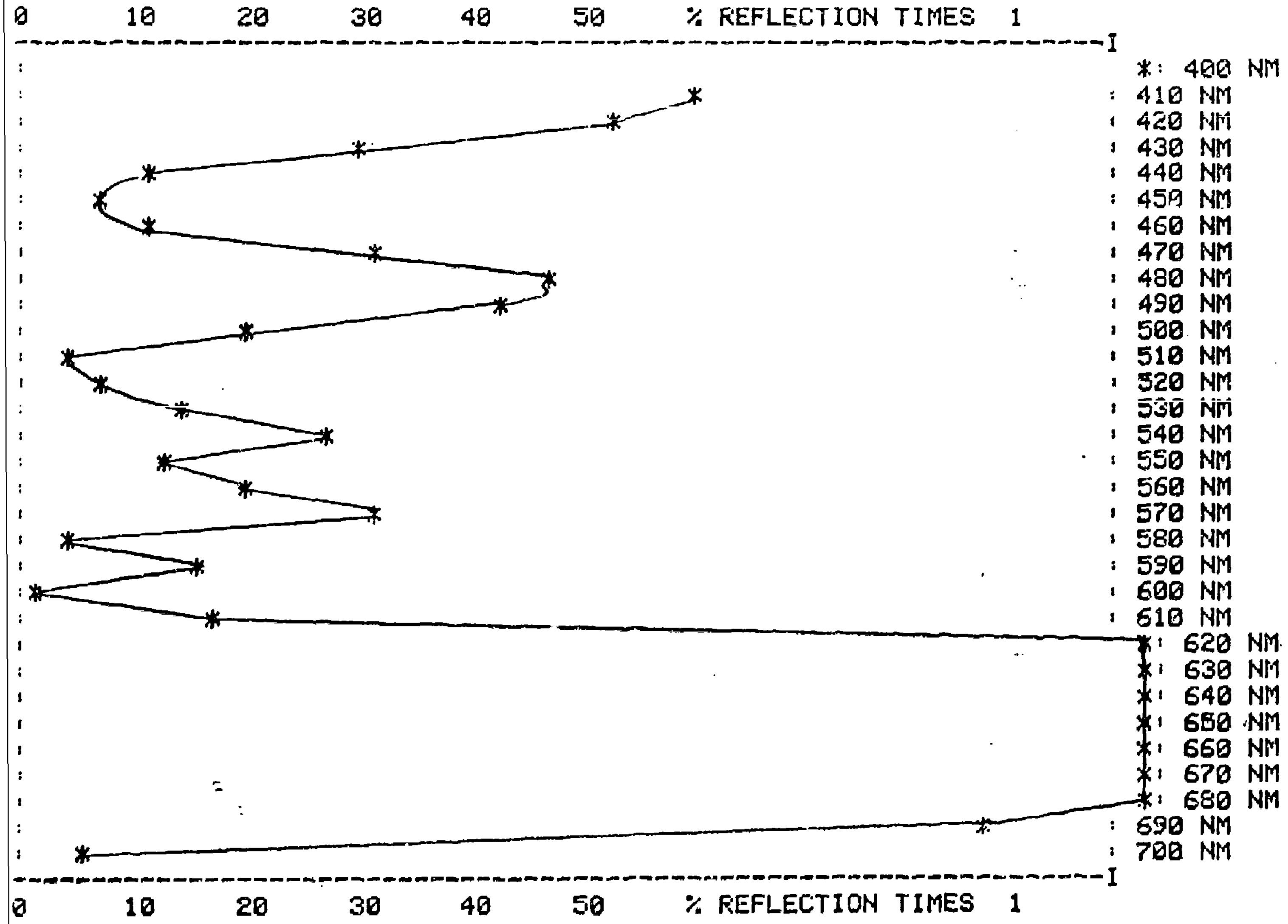
2	1.8	270.8	3
3	2.35	207.4	3
4	1.35	361.1	3
5	2.35	207.4	3
6	1.35	361.1	3
7	2.35	207.4	3
8	1.35	361.1	3
9	2.35	207.4	3
10	1.35	361.1	3
11	2.35	207.4	3
12	1.35	361.1	3
13	2.35	207.4	3
14	1.35	361.1	3
15	2.35	207.4	3
16	1.35	361.1	3
17	2.35	207.4	3
18	1.8	270.8	3
19	2.35	345.7	5



APPENDIX III

WRAP-AROUND GOGGLE CONCEPT